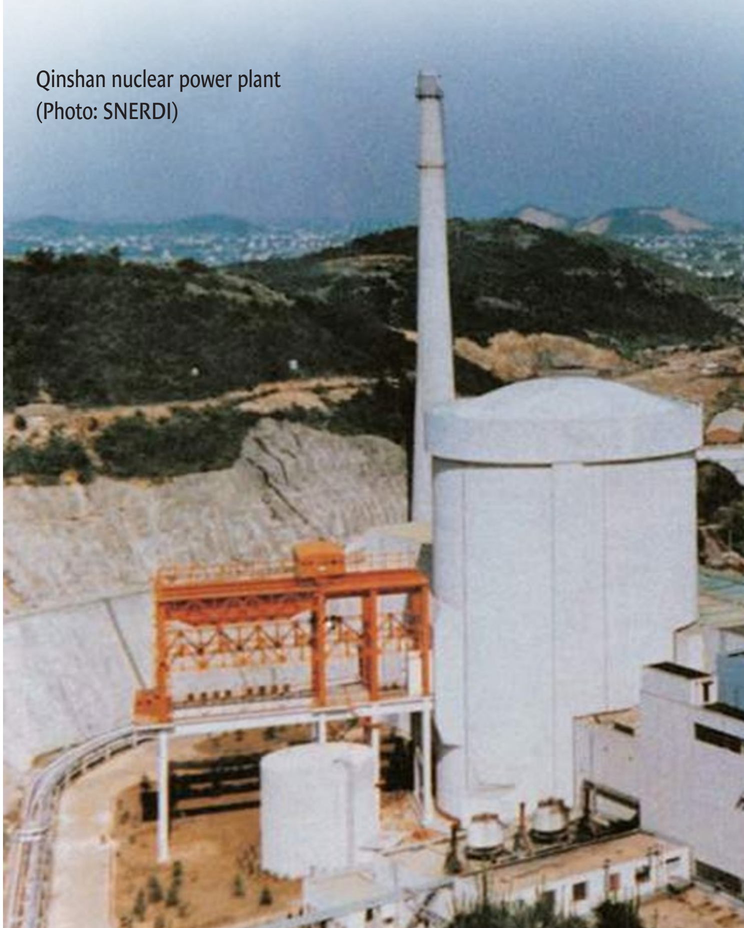
# Nuclear power developments in China and the world

By Mingguang Zheng, Fan Yu, and Li Bao

The development of human society and technology is closely correlated to the means of energy acquisition, utilization method, efficiency, and spectrum of applications. High quality of life and sustainable socioeconomic development require a sustainable and reliable energy supply. Wealth, health, food, water, infrastructure, education, and even life expectancy itself strongly correlate with the consumption of energy per capita. Having an adequate, reliable, affordable, eco-friendly, and sustainable supply of energy is becoming more crucial for economic development and improving human well-being.

Existing energy systems heavily based on fossil fuels face several major challenges, including limited storage and huge carbon emissions. Meanwhile, renewable energy is intermittent and uncertain. To fully support the needs of large power grids, cross-season, cross-time-period, and cross-region problems must be solved with energy storage and transmission or integrated energy systems. However, to date, energy storage and application also face many challenges, including general capacity, efficiency, safety, and economy. In addition, expectations for future power demand are generally inaccurate, considering the availability of resources and technologies and the discrepancy in economic, social, institutional, and cultural aspects.



Qinshan nuclear power plant
(Photo: SNERDI)

Nuclear energy is safe, stable, reliable, clean, and low carbon, benefitting from 70 years of lessons learned and continuous efforts in safety improvement, reliability study, and economic enhancement. It will play an irreplaceable role in the future energy mix.

## Progress and recognition

Beginning with the first self-sustaining nuclear chain reaction at the University of Chicago on December 2, 1943, Gen I nuclear (referring to prototype and testing reactors that launched for civil nuclear power) testified to the feasibility of nuclear reactors. Gen II reactor designs arose in the mid-1960s to demonstrate acceptable economics and safety after more than 10,000 reactor-years of operation. Gen III advanced pressurized water reactors achieved substantial improvement in economy and safety; succeeded in eliminating the possibility of significant release of radioactivity to the public and environment, even in the event of reactor core meltdown; and began large-scale construction in the United States, China, and elsewhere. While commercial demonstration of Gen IV reactors has been launched in some regions, such as the high-temperature pebble-bed reactors in China that were connected to the grid in 2022, considerable fundamental research is still necessary to achieve better economy and initiate industrial applications.

The blueprint of nuclear power in mainland China started with the self-designed Qinshan 300-MWe pressurized water reactor, with an original lifespan of 30 years that was then extended for an additional 20 years. Since the beginning of nuclear power development in China more than 50 years ago, the principle of self-reliance with broad international cooperation has been followed throughout nuclear energy development. China has adhered to its tenet of independence and meanwhile has introduced advanced international safety concepts and technologies. China introduced various reactor technologies based on international technology, such as the M312, which originated from the M310 three-loop design that was developed in France and was based on Westinghouse PWR technology, the water-water energetic reactor (VVER) from Russia, the CANDU-6 PWR from Canada, and the AP1000 PWR from the United States. With various reactor designs, development of nuclear technologies, and operation and management experience from power plants accumulated, China has strategically established an integrated nuclear industrial system, including a complete nuclear industry research and development system, a nuclear supply chain, and an active nuclear market, all of which has helped establish a solid foundation for future development of nuclear power.

By the end of 2022, the nuclear power reactors in mainland China had accumulated more than 500 combined reactor-years of operation. Various international peer reviews indicate that the Chinese nuclear power industry has the unprecedented eagerness to achieve world's best standards of excellence in nuclear safety, power generation management, power plant equipment reliability, regulatory effectiveness, and industrial safety.

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## R&D of advanced PWRs

In the past 15 years, based on its well-established nuclear power and machinery industries, as well as introduction, digestion, absorption, and innovation of advanced nuclear technologies, China—with strong support from the United States—has built four Westinghouse AP1000 units (two each in Sanmen and Haiyang) and has developed two designs of advanced PWRs: CAP1400 and Hualong-1. CAP1400 comprehensively inherits the passive safety and system simplification philosophy with enhanced reactor safety. Hualong-1 stems from the CNP1000 design, which was based on M310 with additional passive systems and functions.

The two main safety performance or risk metrics of CAP1400—the core damage frequency (CDF; $2.4\times10^{-7}$ per reactor-year) and large release frequency (LRF; $5.07\times10^{-7}$ per reactor-year)—are greatly enhanced from previous reactors. Conforming to the safety and availability goals, CAP1400 is two to three orders of magnitude safer than general Gen II reactors, which is to say that the risks of 400 CAP1400 units are equivalent to the risk of one unit of a representative Gen II reactor.

CAP1400 has a systematic severe accident prevention and mitigation strategy, offering a 72-hour "grace period" with no active intervention required, thanks to the passive or inherent safety features that rely on gravity, natural convection, or resistance to high temperatures. The passive systems are designed to remove heat from the reactor and containment under accident conditions, forming better resistance to damage from possible core meltdown and confinement of radioactivity. Technically, emergency evacuation is not required, because the probability of significant radioactive release under any core meltdown is extremely low, and there would be no serious harm to the public. Following lessons learned from the Fukushima accident and informed by the ensuing updated regulatory policies, China developed more robust reactor designs to achieve optimal safety and implemented natural circulation/convection cooling features to the reactor core. The "defense-in-depth" approach ensures the reactor is capable of coping with extreme flooding and seismic conditions, and cooling water and electrical power supplies after a postulated accident would be initiated. Even in the event of extreme external disasters, CAP1400 can fully ensure safety.

In addition to developing advanced PWRs, China also continues to strengthen R&D support for multi-application small modular reactors, molten salt reactors, and fast reactors and is actively carrying out commercial reactor demonstration. Application of nuclear energy in China is changing from simply generating electric power to versatile applications, including district heating, process heat, desalination, hydrogen generation, and so on. On November 9, 2021, Haiyang in Shandong Province became the first city in China to achieve net zero carbon in district heating, as it is fully heated by warm water from the heat exchangers installed downstream of the high-pressure turbine of the Haiyang nuclear power plant.

Haiyang nuclear power plant
(Photo: SNERDI)

CAP1400 nuclear power plant concept diagram (Image: SNERDI)

## SMRs in China

In addition to large advanced PWRs, China is also continuing to develop multipurpose SMRs for different application scenarios, including advanced water-cooled; high-temperature, gas-cooled; sodium- or lead-cooled, fast neutron–spectrum; and molten salt reactors.

Advanced water-cooled reactors can be tailored to different market demands covering land- and marine-based designs. CAP200, an advanced passive PWR, is being used for nuclear cogeneration and diesel generator replacement. An integrated heating reactor with an "intelligent heating concept" has been initiated by the State Power Investment Corporation. Linglong One, an ACP100 300-MWt PWR, and Yanlong, a DHR400 pool-type low-temperature heating reactor, are being developed by the China National Nuclear Corporation. The floating nuclear power plant ACPR50S was created by China General Nuclear Power, and NHR200-II is a 200-MW nuclear heating reactor designed by Tsinghua University. SMRs in China are being developed based on technologies proven through engineering practices with higher inherent safety that are suitable for partial or dedicated use in nonelectric applications, such as district heating, providing heat for industrial processes, hydrogen production, or seawater desalination. To date, the construction of Linglong One is being carried out in Changjiang, in Hainan Province, and other SMRs are being prepared for commercial implementation.

The Gen IV International Forum (GIF) has led to international collaborative efforts to develop next-generation nuclear energy systems and selected six reactor technologies for further research and development: the gas-cooled fast reactor (GFR), the lead-cooled fast reactor (LFR), the molten salt reactor (MSR), the supercritical water-cooled reactor (SCWR), the sodium-cooled fast reactor (SFR), and the very-high-temperature reactor (VHTR). China has launched principal verification and prototype research and is poised to make advances in all six areas. The demonstration high-temperature, gas-cooled reactor pebble-bed module (HTR-PM) at the Shidaowan nuclear plant in Shandong Province has reached initial full power in 2022; two CFR600 600-MW sodium-cooled, pool-type fast-neutron reactors (CFR600) are currently under construction; and TMSR-LF1, a 2-MW liquid fuel, thorium-based molten salt experimental reactor, is providing commercial electricity in Wuwei, Gansu Province, with testing to follow. China's first lead-bismuth alloy zero-power reactor, Qixing (Venus) III, achieved first criticality in 2019, and the China Institute of Atomic Energy is devoted to construction of a lead-bismuth, accelerator-driven test facility. Gas-cooled fast reactors and supercritical water-cooled reactors are still in the research phase and have not made significant progress yet.

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Sanmen nuclear power plant
(Photo: SNERDI)

## Forging an advanced supply chain

Chinese power grids heavily relied on fossil fuels for power at the beginning of the 21st century and confront four challenges mentioned above. To adjust the energy structure and reduce the share of fossil fuels in power generation, China has implemented a National Science and Technology Major Project to support nuclear power development to strengthen the country's capabilities in basic materials, equipment manufacturing, industrial support, and other aspects, with the goal to gradually establish a full-scale advanced supply chain to support advanced PWR deployment.

More than 30,000 scientists and engineers across 700-plus institutions are engaged in the development of the CAP1400 and its materials and equipment supply to support its deployment. Large, key companies, local businesses, national research institutions, colleges and universities, and outstanding private enterprises are coordinating to complete the missions of R&D, design, verification and validation, software and standards, safety evaluation, equipment manufacturing, construction and installation, and operation and maintenance. China now has the capability to construct more than 10 reactor units annually, including equipment manufacturing and supply, which enables strong support of future mass and large-scale nuclear reactor construction.

The availability of skilled staff is vital to the sustainability of the nuclear energy sector. From education to training and practical experience, including domestic and international communication and collaboration, China is endeavoring to grow, improve, and retain nuclear sector talent. Primary and high school students are engaged in STEM courses, and universities concentrate on scientific research and strengthening collaboration with nuclear enterprises and research institutes for on-site training programs. Mentoring training strategies are generally adopted to cultivate specific talents in different areas, subjects, or majors. Talent is diversified and compounded by rotating assignments and temporary positions in different sectors or companies.

China is consistently improving the capabilities of the nuclear workforce and shaping the competitive talents of the pool. Learning from the training and talent that emerged during the construction of the Qinshan nuclear power project and continuing after the implementation of the National Science and Technology Major Project, China has realized the importance of highly competitive human resources. A qualified and competent nuclear team is built through years of research and development of advanced reactors and fleet construction. Conservative R&D and our five-decade history of nuclear plant construction have been crucial for the maintenance of our nuclear industry talent.

With continued R&D, plant construction, and increasing capability in the global nuclear industry, China has become one of the few countries with complete and advanced manufacturing capabilities. We also have the highly talented workforce in large enough numbers to support high-quality development of all sectors of the industry. This makes China well positioned to contribute to the development of global nuclear power.

# High-operation nuclear safety

The world will need a significantly increased energy supply in the future—especially clean electricity. An important energy source that can provide carbon-free baseload power, nuclear will play a larger and more consequential role in meeting global energy needs in a carbon-constrained world. Reliable and safe operation is the lifeline of nuclear energy development, and there are no national boundaries in nuclear safety. The nuclear accidents at Three Mile Island, Chernobyl, and Fukushima Daiichi over the years have had a significant, negative impact on the development of global nuclear power, leading to long periods of stagnation. A new severe accident in any country would threaten every existing nuclear power sector.

Without nuclear power safety, there is no future for nuclear power. Safe and sustainable development of nuclear power is the mission and responsibility of any nuclear power industry and every government. And no one in the industry is exempt from the obligation to ensure the highest standards of reactor safety. Nuclear safety depends on the joint efforts of the global nuclear power industry. All of us must fully understand the importance of nuclear safety and establish a global nuclear safety culture. We should always adhere to the principle of nuclear safety first, according to the concepts of defense-in-depth and multiple barriers. We should research, design and develop, and promote safer and more advanced reactor technology; strictly manage the safety activities of the whole life cycle of nuclear power to guard against the possibility of a spectrum of accidents; and ensure the absolute safety of operations. We should also actively explore and research spent fuel reprocessing technologies and paths for uranium utilization efficiency, including transportation, long-term storage, and geologic disposal. In addition, public communication and the promotion of nuclear energy must be better handled, with accurate and fact-based information about nuclear energy made easily accessible to regain public acceptance and trust. In short, nuclear safety should be ensured from all aspects.

Nuclear power has a long record of contributing to a diversified energy supply in a resilient and sustainable manner. Through the continuous efforts of scientists and engineers in the global nuclear power industry, the safety, reliability, economics, and availability of nuclear power have been greatly improved; cost-competitiveness has been enhanced; and risks have been significantly reduced. Nuclear is the ultimate energy that guarantees the sustainable development of human society. A commitment made by the whole industry to inherent safety, innovative technologies, and increased public awareness and acceptance will promote the long-term development of nuclear energy in the future and support the global realization of the zero-carbon goal.

*Mingguang Zheng is chief engineer of nuclear at State Power Investment Company and chief designer of the CAP1400 large advanced PWR. Fan Yu is a senior engineer at Shanghai Nuclear Engineering Research & Design Institute and head of the working team of the Office of the Chief Designer of the National Science and Technology Key Special Project for PWR. Li Bao is an economist at the Shanghai Nuclear Engineering Research & Design Institute.*

Daya Bay nuclear power plant
(Photo: SNERDI)